

# Cosmological Tests Using X-ray Observations of Clusters of Galaxies

Adam Mantz (Stanford/SLAC)

with Steve Allen, Harald Ebeling (Hawaii), David Rapetti, Robert Schmidt (Heidelberg), Glenn Morris, Andy Fabian (Cambridge), Doug Applegate, Maruša Bradač (UCSB), Evan Million, Anja von der Linden, Patrick Kelly and Alex Drlica-Wagner

Fermilab Particle Astrophysics Seminar

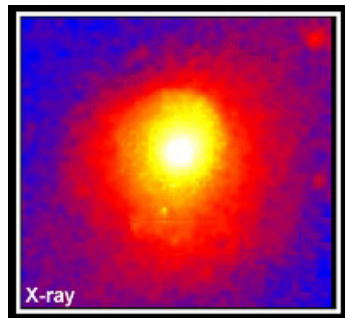
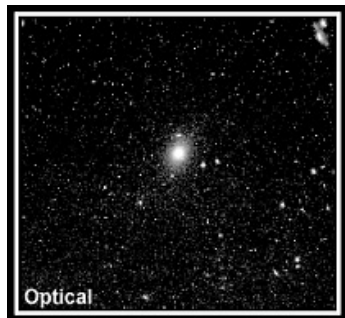
January 5, 2009



# Introduction

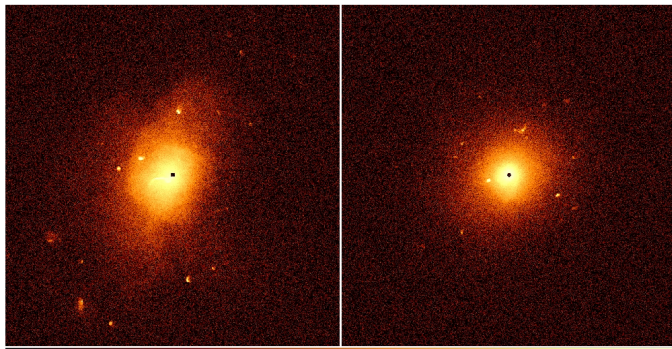
## Why study clusters in X-rays?

- ▶ Most of the luminous matter in clusters is gas in the intracluster medium, not galaxies. In massive clusters, this gas is hot enough to radiate brightly in X-rays.
- ▶ Since X-ray luminosity depends strongly on gas density, X-ray surveys are a great way to find big clusters for cosmology.
- ▶ Primary observables (density, temperature) are closely related to the gravitational potential (total mass).



## Introduction

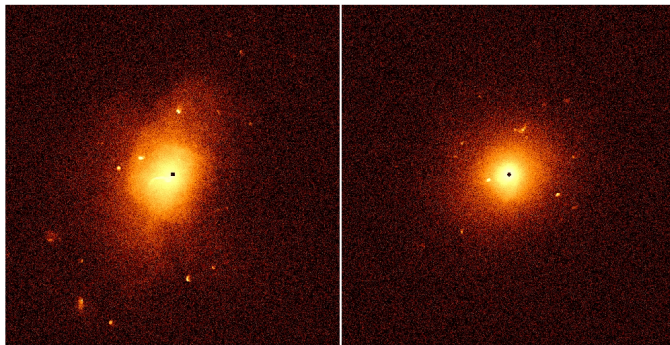
The downside: deriving interesting cluster properties from X-ray observations requires the assumption that the gas is in hydrostatic equilibrium. Simulations and mock-image analysis indicate that this biases results.



Nagai *et al.* 2007

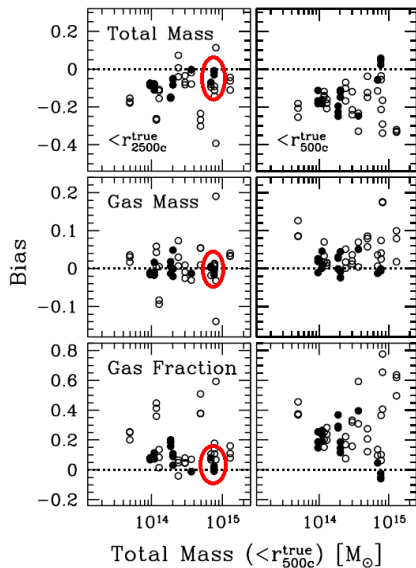
# Introduction

The upside: the same simulations indicate that these systematics are both **quantifiable** and **manageable**.



Nagai *et al.* 2007

# Introduction



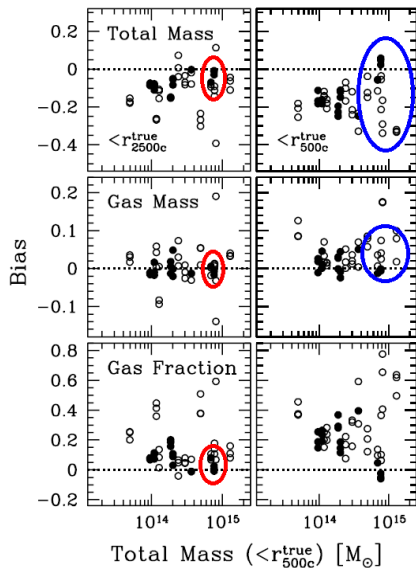
For largest relaxed clusters, we can measure at  $r_{2500}$

- $M_{\text{gas}}$  to  $\sim 1\%$  accuracy
- $M_{\text{tot}}$  to few % accuracy

Bias and scatter are primarily due to non-thermal pressure support (bulk motions).

← Nagai *et al.* 2007  
filled circles = relaxed clusters

# Introduction



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- $M_{\text{gas}}$  to  $\sim 1\%$  accuracy
- $M_{\text{tot}}$  to few % accuracy

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For the general population at  $r_{500}$

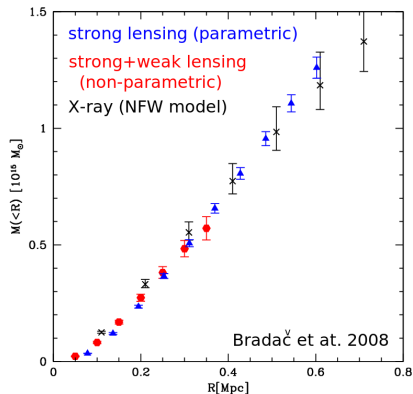
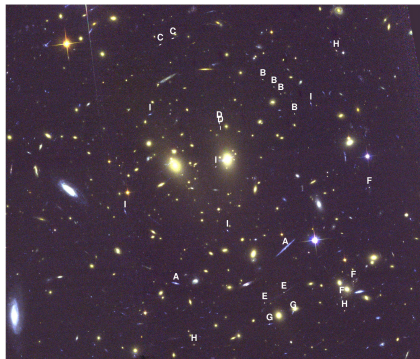
- $M_{\text{gas}}$  is still recovered to few %
- $M_{\text{tot}}$  is underestimated by 20–30%

← Nagai *et al.* 2007

filled circles = relaxed clusters

# Introduction

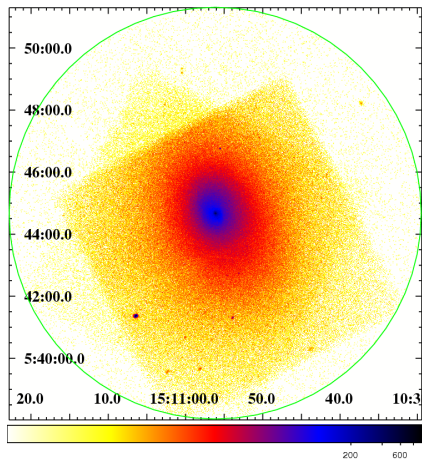
Gravitational lensing provides another handle.



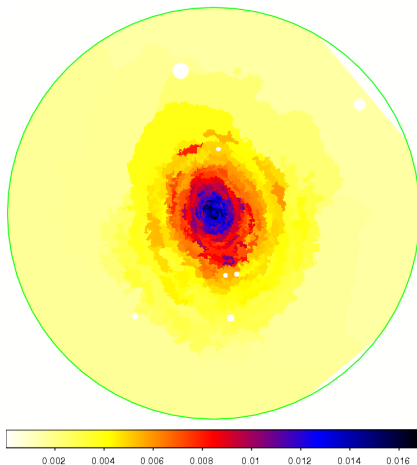
RXJ1347-1145 ( $z = 0.45$ )

# Introduction

What does relaxed mean?



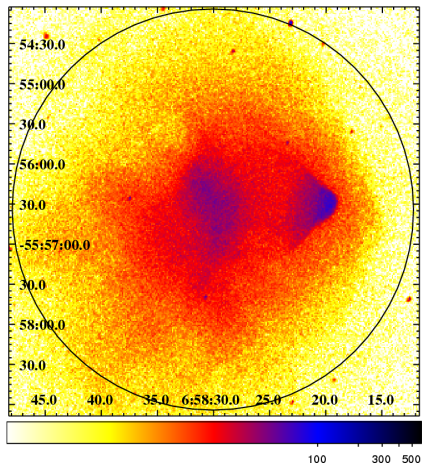
Million & Allen 2008



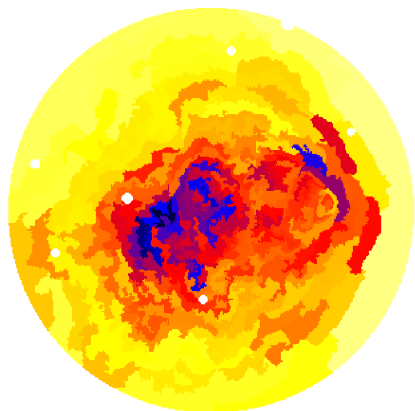
Abell 2029

# Introduction

What does unrelaxed mean?



Million & Allen 2008



1E0657-56

# Outline

## Cluster gas-mass fraction

- Measuring  $\Omega_m$  with local observations

- Constraining dark energy:  $f_{\text{gas}}$  as a standard ruler

## Growth of structure

- Ingredients: the mass function and cluster scaling relations

- Constraints on dark matter and dark energy

- Tests of General Relativity

*Allen et al. 2008, MNRAS, 383, 879*

(See also e.g. White & Frenk '91; Fabian '91; Briel *et al.* '92; White *et al.* '93; David *et al.* '95; White & Fabian '95; Evrard '97; Mohr *et al.* '99; Ettori & Fabian '99; Roussel *et al.* '00; Grego *et al.* '00; Ettori *et al.* '03; Sanderson *et al.* '03; Lin *et al.* '03; LaRoque *et al.* '06; Allen *et al.* '02, '04.)

$f_{\text{gas}}$ : measuring  $\Omega_{\text{m}}$  with local observations

*Fair sample hypothesis*: galaxy clusters are so large that their matter content is approximately a fair sample of the matter content of the Universe (White & Frenk 1991).

For relaxed clusters, gas mass and total mass can be measured accurately with X-rays.

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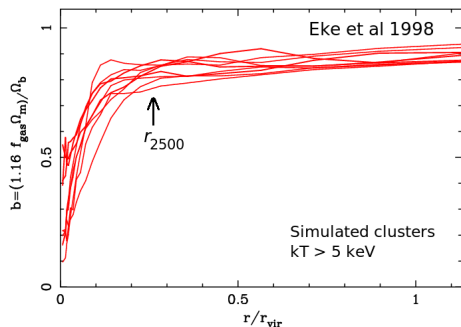
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Fair sample:  $f_{\text{baryon}} = b \Omega_{\text{b}}/\Omega_{\text{m}}$ .

$$f_{\text{gas}} = \frac{f_{\text{baryon}}}{1 + s} = \frac{b}{1 + s} \left( \frac{\Omega_{\text{b}}}{\Omega_{\text{m}}} \right)$$

## $f_{\text{gas}}$ : measuring $\Omega_m$ with local observations

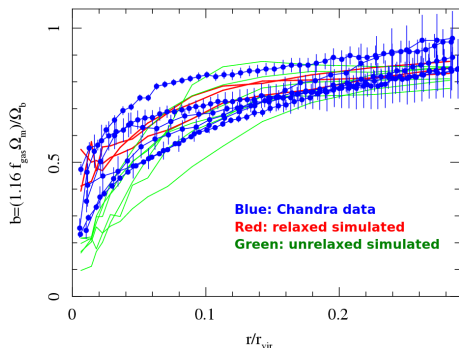


Non-radiative simulations indicate

$$b = f_{\text{baryon}} \frac{\Omega_m}{\Omega_b} = 0.83 \pm 0.09$$

(+ 10% systematic uncertainty) at  $r_{2500}$ .

## $f_{\text{gas}}$ : measuring $\Omega_{\text{m}}$ with local observations



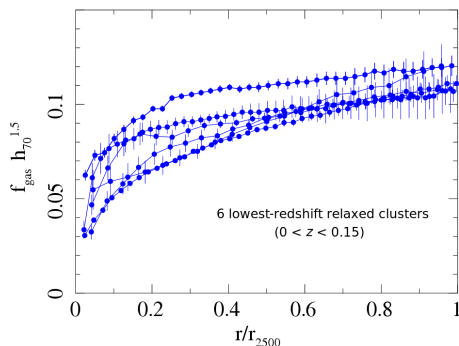
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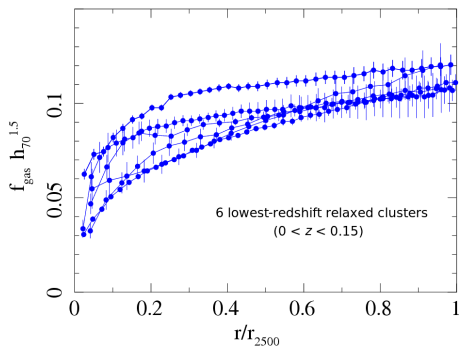
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Constant fit to the data:

$$f_{\text{gas}}(r_{2500}) = (0.113 \pm 0.003) h_{70}^{-1.5}$$

## $f_{\text{gas}}$ : measuring $\Omega_{\text{m}}$ with local observations



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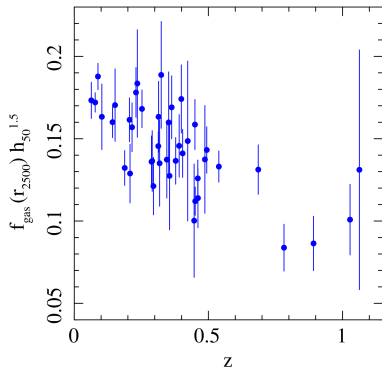
Using  $\Omega_{\text{b}} h^2 = 0.0214 \pm 0.002$  (Kirkman *et al.* '03),  $h = 0.72 \pm 0.08$  (Freedman *et al.* '01),  $s = (0.16 \pm 0.048) h_{70}^{1/2}$  (e.g. Lin & Mohr '04),  $b = 0.83 \pm 0.09$  (Eke *et al.* '98 +10% systematic allowance),

$$\Omega_{\text{m}} = \frac{b \Omega_{\text{b}}}{f_{\text{gas}}(1 + s)} = 0.27 \pm 0.04$$

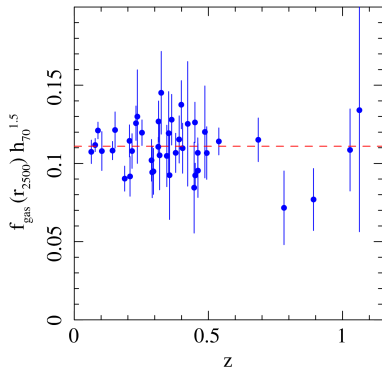
## $f_{\text{gas}}$ as a standard ruler

Measured  $f_{\text{gas}}$  values depend on the assumed distances to clusters as  $f_{\text{gas}} \sim d^{3/2}$ . This makes the apparent  $f_{\text{gas}}(z)$  dependent on cosmological parameters.

SCDM ( $\Omega_m = 1.0$ ,  $\Omega_\Lambda = 0.0$ )



$\Lambda$ CDM ( $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ )

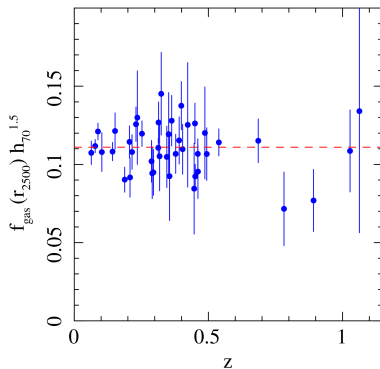
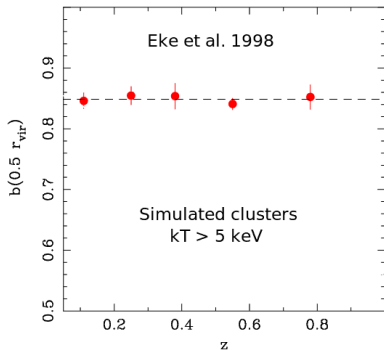


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Expectation: approximately constant with redshift

$\Lambda$ CDM ( $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ )

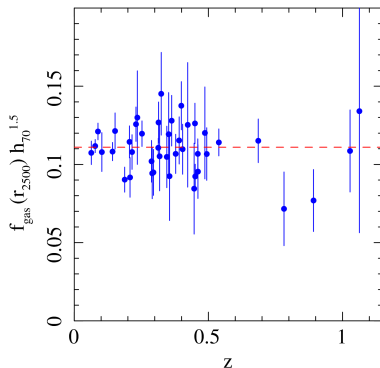
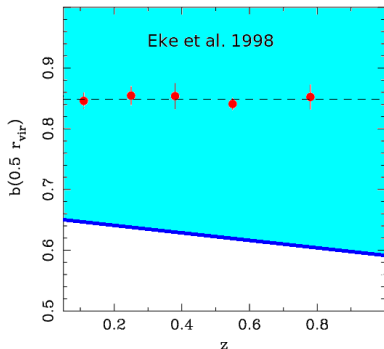


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$\Lambda$ CDM ( $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ )



## $f_{\text{gas}}$ as a standard ruler

The full model:

$$f_{\text{gas}}^{\text{ref}}(z) = K\gamma \left[ \frac{b(z)}{1+s(z)} \right] \left( \frac{\Omega_{\text{b}}}{\Omega_{\text{m}}} \right) \left( \frac{\theta_{2500}^{\text{ref}}}{\theta_{2500}^{\text{trial}}} \right)^{\eta} \left[ \frac{d^{\text{ref}}(z)}{d^{\text{trial}}(z)} \right]^{3/2}$$

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Conservative systematic allowances used:

$K$  : Instrument calibration, X-ray modeling

10% Gaussian uncertainty

$\gamma$  : Non-thermal pressure support in gas (primarily bulk motions)

$\gamma = M_{\text{est}}/M_{\text{true}}$

10% uniform prior,  $1 < \gamma < 1.1$

## $f_{\text{gas}}$ as a standard ruler

The full model:

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Conservative systematic allowances used:

$b(z)$  : Depletion factor (simulation physics, gas clumping)

$$b(z) = b_0(1 + \alpha_b z)$$

$\pm 20\%$  uniform prior on  $b_0$

$\pm 10\%$  uniform prior on  $\alpha_b$

$s(z)$  : Baryonic mass in stars (observational uncertainty)

$$s(z) = s_0(1 + \alpha_s z) = f_{\text{star}}/f_{\text{gas}}$$

30% Gaussian uncertainty on  $s_0$

$\pm 20\%$  uniform prior on  $\alpha_s$

## $f_{\text{gas}}$ as a standard ruler

The full model:

$$f_{\text{gas}}^{\text{ref}}(z) = K\gamma \left[ \frac{b(z)}{1+s(z)} \right] \left( \frac{\Omega_b}{\Omega_m} \right) \left( \frac{\theta_{2500}^{\text{ref}}}{\theta_{2500}^{\text{trial}}} \right)^{\eta} \left[ \frac{d^{\text{ref}}(z)}{d^{\text{trial}}(z)} \right]^{3/2}$$

$\Omega_b$  : Baryon density (independent data)

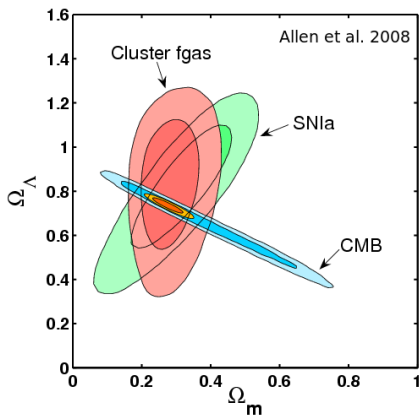
$$\Omega_b h^2 = 0.0214 \pm 0.002 \text{ (Kirkman } et al. '03)$$

$$h = 0.72 \pm 0.08 \text{ (Freedman } et al. '01)$$

$\eta$  : slope of  $f_{\text{gas}}(r)$  at  $r_{2500}$  (measured)

10% Gaussian uncertainty

## $f_{\text{gas}}$ : results for $\Lambda$ CDM models



$f_{\text{gas}}$ : 42 clusters with standard priors

CMB: WMAP3+CBI+ACBAR  
+ prior  $0.2 < h < 2$

Supernovae: 192 from Davis '07  
(ESSENCE+SNLS+HST+nearby)

Combination does not require  $\Omega_b h^2$ ,  $h$   
priors.

$f_{\text{gas}}$  alone:

$$\Omega_m = 0.27 \pm 0.06$$

$$\Omega_\Lambda = 0.86 \pm 0.119$$

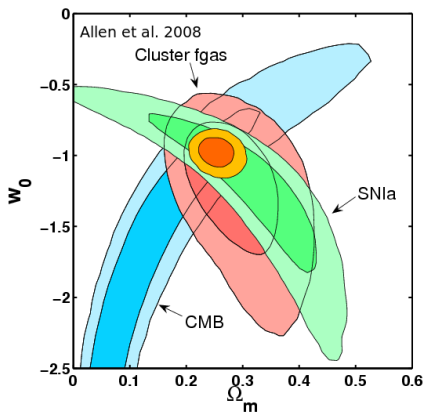
Combination:

$$\Omega_m = 0.275 \pm 0.033$$

$$\Omega_\Lambda = 0.735 \pm 0.023$$

Goodness of fit:  $\chi^2_\nu = 41.5/40$

## $f_{\text{gas}}$ : results for flat, constant- $w$ models



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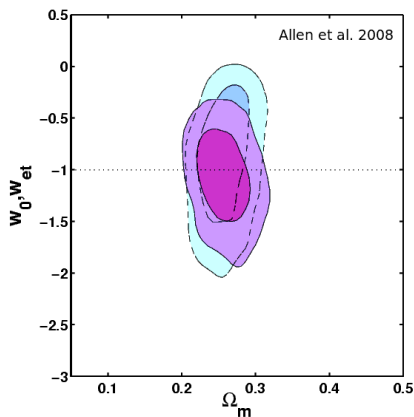
$f_{\text{gas}}$  alone:

$$\begin{aligned}\Omega_m &= 0.28 \pm 0.06 \\ w &= -1.14^{+0.27}_{-0.35}\end{aligned}$$

Combination:

$$\begin{aligned}\Omega_m &= 0.253 \pm 0.021 \\ w &= -0.98 \pm 0.07\end{aligned}$$

## $f_{\text{gas}}$ : results for flat, evolving- $w$ models



$$w(z) = \frac{w_0 z_t + w_{et} z}{z + z_t}$$

Marginalized over the transition redshift  
 $0.5 < 1/(1 + z_t) < 0.95$

Using

$f_{\text{gas}}$ : 42 clusters with standard priors

CMB: WMAP3+CBI+ACBAR  
+ prior  $0.2 < h < 2$

Supernovae: 192 from Davis '07  
(ESSENCE+SNLS+HST+nearby)

Combination does not require  $\Omega_b h^2$ ,  $h$   
priors.

Results are consistent with  $\Lambda$ CDM

$$\begin{aligned} w_0 &= -1.05^{+0.31}_{-0.26} \\ w_{et} &= -0.83^{+0.48}_{-0.43} \end{aligned}$$

# Outline

## Cluster gas-mass fraction

- Measuring  $\Omega_m$  with local observations

- Constraining dark energy:  $f_{\text{gas}}$  as a standard ruler

## Growth of structure

- Ingredients: the mass function and cluster scaling relations

- Constraints on dark matter and dark energy

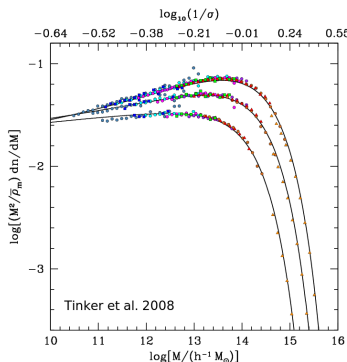
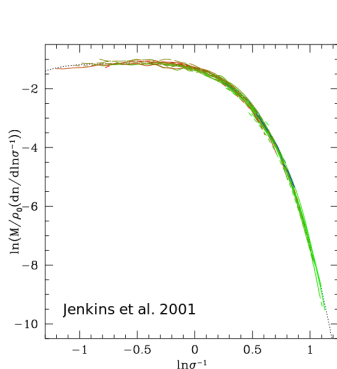
- Tests of General Relativity

Mantz *et al.* 2008, MNRAS, 387, 1179

Rapetti *et al.* 2008, arXiv:0812.2259

(See also e.g. Henry '00; Borgani *et al.* '01; Reiprich & Böhringer '02; Seljak '02; Viana *et al.* '02; Allen *et al.* '03; Pierpaoli *et al.* '03; Vikhlinin *et al.* '03; Schuecker *et al.* '03; Voevodkin & Vikhlinin '04; Henry '04; Dahle '06, Henry *et al.* '08, Vikhlinin *et al.* '08)

## Growth of structure: theoretical prediction

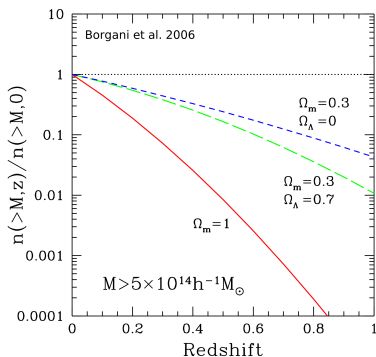
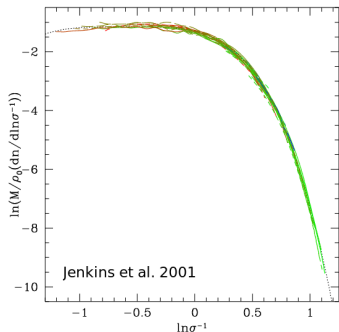


Suites of cosmological simulations predict cluster density  $\left\langle \frac{dn}{dM dz} \right\rangle$ .

The mass function can be written in universal form (within 10–20% across a range of tested cosmological models) in terms of  $\sigma(M, z)$ , where

$$\sigma^2(M, z) = \frac{1}{2\pi^2} \int_0^\infty k^2 P(k, z) |W_M(k)|^2 dk$$

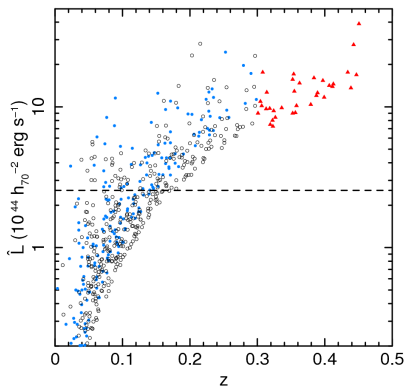
## Growth of structure: theoretical prediction



Once the normalization ( $\sigma_8$ ) is measured, the evolution of the mass function can be used to learn about dark energy.

## Growth of structure: X-ray luminosity function

Main observable: a wide-area, clean, complete cluster sample with a well understood selection function.



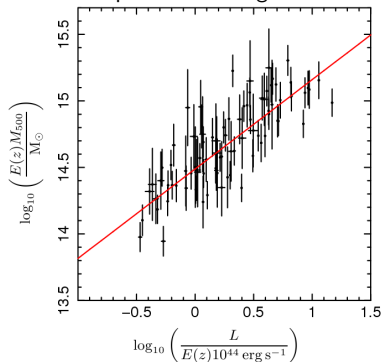
Samples based on the ROSAT All-Sky Survey:

- ▶ BCS (Ebeling *et al.* '98, '00)  
 $z < 0.3$   
 $\sim 33\%$  sky coverage  
 $F > 4.4 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$
- ▶ REFLEX (Böhringer *et al.* '04)  
 $z < 0.3$   
 $\sim 33\%$  sky coverage  
 $F > 3.0 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$
- ▶ MACS (Ebeling *et al.* '01, '07)  
 $0.3 < z < 0.7$   
 $\sim 55\%$  sky coverage  
 $F > 2.0 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$

Luminosity cut at  $2.55 \times 10^{44} h_{70}^{-2} \text{ erg s}^{-1}$  leaves  
 $78 + 130 + 34 = 242$  massive clusters.

## Growth of structure: scaling relation

Data of Reiprich & Böhringer '02



Self-similarity suggests a power-law model

$$Y = \alpha + \beta X_1$$

where

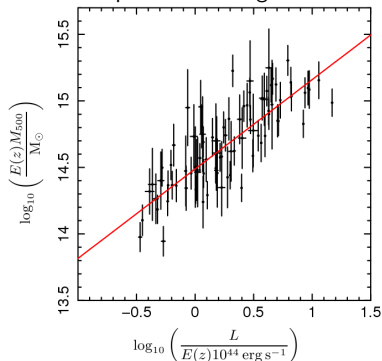
$$Y = \log_{10}\left(\frac{E(z)M_{500}}{M_{\odot}}\right)$$

$$X_1 = \log_{10}\left(\frac{L}{E(z)10^{44} \text{ erg s}^{-1}}\right)$$

and the factors of  $E(z) = H(z)/H_0$  are due to the evolution in  $r_{500}$ .

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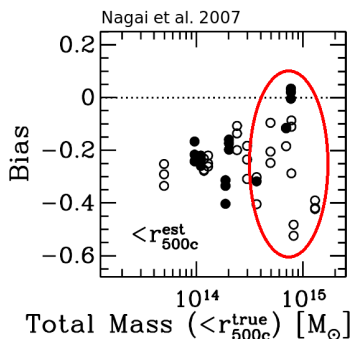
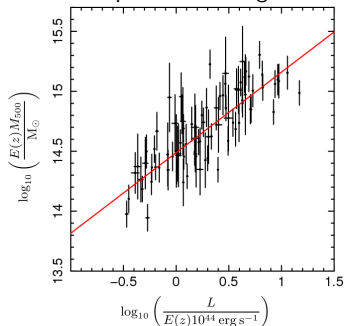
Marginalize over possible deviations from self-similarity:

$$Y = \alpha + \beta X_1 + \gamma X_2$$

$$X_2 = \log_{10}(1 + z)$$

## Growth of structure: scaling relation

Data of Reiprich & Böhringer '02



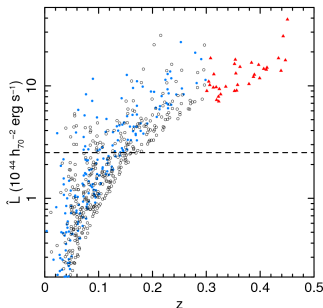
$M$ ,  $L$  from X-ray observations (Reiprich & Böhringer '01). Departures from hydrostatic equilibrium introduce a bias in the estimates of  $r_{500}$ ,  $M_{500}$ .

Based on simulations, marginalize over bias  $-25(\pm 5)\%$  and scatter  $\pm 15(\pm 3)\%$ .

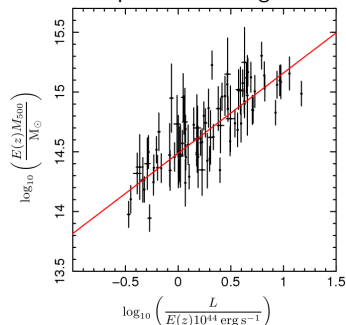
A problem, but major improvements are possible. . . in preparation.

# Growth of structure: analysis sketch

BCS+REFLEX+MACS



Data of Reiprich & Böhringer '02



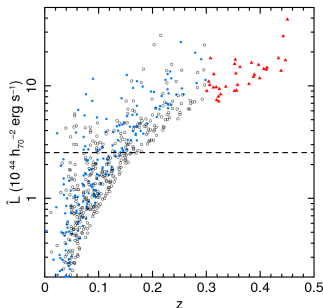
Compare the survey data (redshifts, fluxes) with the expectation:

$$\left\langle \frac{dN(z, \hat{L})}{dz d\hat{L}} \right\rangle = P_{\text{sel}}(z, \hat{L}) \int_0^{\infty} dL P(\hat{L}|L) \int_0^{\infty} dM P(L|M) \left\langle \frac{dn(z, M)}{dM} \right\rangle \frac{dV}{dz}$$

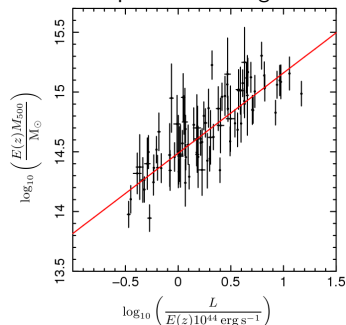
selection function

# Growth of structure: analysis sketch

BCS+REFLEX+MACS



Data of Reiprich & Böhringer '02



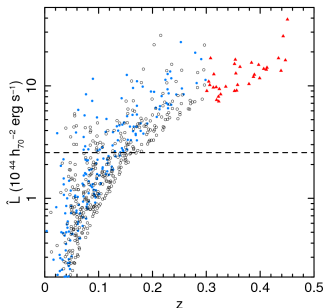
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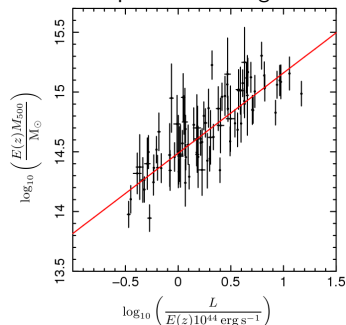
flux measurement error

# Growth of structure: analysis sketch

BCS+REFLEX+MACS



Data of Reiprich & Böhringer '02



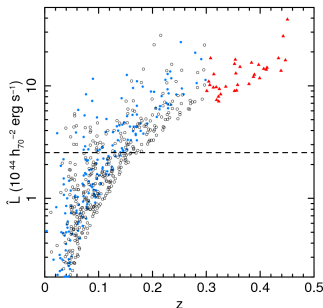
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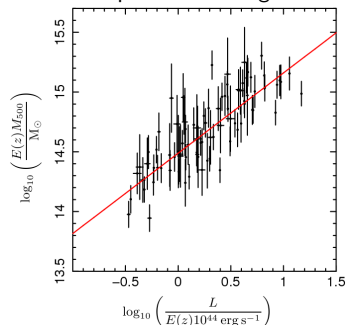
mass–luminosity intrinsic scatter

# Growth of structure: analysis sketch

BCS+REFLEX+MACS



Data of Reiprich & Böhringer '02



Compare the survey data (redshifts, fluxes) with the expectation:

$$\left\langle \frac{dN(z, \hat{L})}{dz d\hat{L}} \right\rangle = P_{\text{sel}}(z, \hat{L}) \int_0^{\infty} dL P(\hat{L}|L) \int_0^{\infty} dM P(L|M) \left\langle \frac{dn(z, M)}{dM} \right\rangle \frac{dV}{dz}$$

mass function and volume element

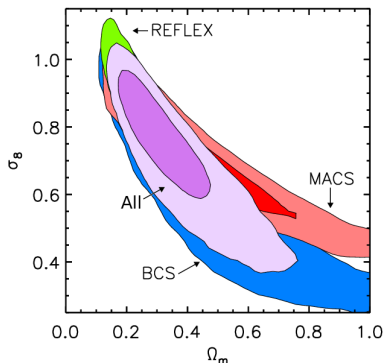
## Growth of structure: priors and systematic allowances

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Cosmological parameters		
Hubble constant, $h$	$0.72 \pm 0.08$	Hubble Key
Baryon density, $\Omega_b h^2$	$0.0214 \pm 0.002$	BBN
Mass function		
normalization	$\pm 20\%$	Gaussian
Mass–luminosity relation		
non-similar evolution	$\pm 20\%$	uniform
scatter evolution	$\pm 30\%$	uniform
mass bias and scatter	$\pm 20\%$	Gaussian

---

## Growth of structure: results for flat $\Lambda$ CDM models



Results from the 3 cluster samples individually are consistent with one another, and with most previous work using clusters.

$$\text{BCS} \quad \Omega_m = 0.26^{+0.25}_{-0.09}$$

$$\sigma_8 = 0.78^{+0.10}_{-0.37}$$

$$\text{REFLEX} \quad \Omega_m = 0.20^{+0.10}_{-0.04}$$

$$\sigma_8 = 0.85^{+0.10}_{-0.09}$$

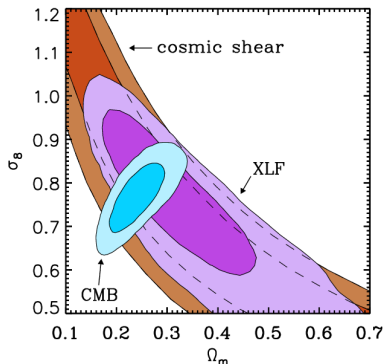
$$\text{MACS} \quad \Omega_m = 0.30^{+0.24}_{-0.10}$$

$$\sigma_8 = 0.73^{+0.14}_{-0.13}$$

$$\text{Combination} \quad \Omega_m = 0.28^{+0.11}_{-0.07}$$

$$\sigma_8 = 0.78^{+0.11}_{-0.13}$$

## Growth of structure: results for flat $\Lambda$ CDM models



Results agree with independent cosmological data.

XLF: 242 clusters,  $z < 0.7$

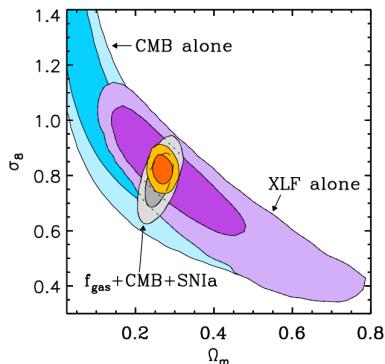
$$\Omega_m = 0.28^{+0.11}_{-0.07}$$

$$\sigma_8 = 0.78^{+0.11}_{-0.13}$$

CMB: WMAP3 data

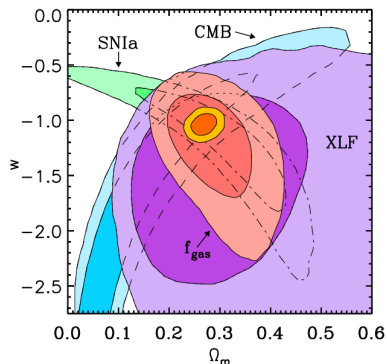
Cosmic shear: CFHTLS Wide, linear regime  
(Fu *et al.* '08)

## Growth of structure: results for flat constant- $w$ models



From the XLF:

$$\begin{aligned}\Omega_m &= 0.24^{+0.15}_{-0.07} \\ \sigma_8 &= 0.85^{+0.13}_{-0.20} \\ w &= -1.4^{+0.4}_{-0.7}\end{aligned}$$

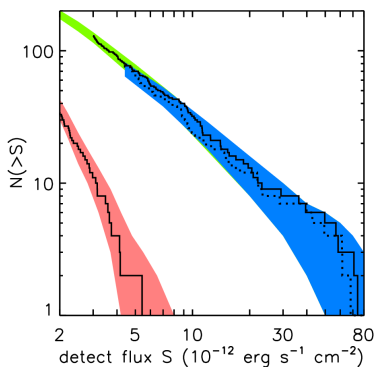


From the combination:

$$\begin{aligned}\Omega_m &= 0.269 \pm 0.016 \quad (0.258 \pm 0.022) \\ \sigma_8 &= 0.82 \pm 0.03 \quad (0.79 \pm 0.06) \\ w &= -1.02 \pm 0.06 \quad (-0.99 \pm 0.07)\end{aligned}$$

Combined results are consistent with  $\Lambda$ CDM.

## Growth of structure: goodness of fit



Observed number as a function of flux limit compared with predictions the  $\Lambda$ CDM best fit for each survey.

# Testing general relativity with the growth of structure

Growth of density perturbations

$\delta = (\rho_m - \bar{\rho}_m)/\bar{\rho}_m$  in GR:

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = 4G\pi\rho_m\delta$$

Instead, parametrize through

$$\frac{d\delta}{da} = \frac{\delta}{a}\Omega_m(a)^\gamma$$

with  $\gamma \sim 0.55$  accurately reproducing GR.

The growth function in this model

- ▶ matches GR at early times
- ▶ has the same scale dependence as GR
- ▶ is allowed to have a different time dependence

On smaller scales, gravity is unmodified.

# Testing general relativity with the growth of structure

Growth of density perturbations

$\delta = (\rho_m - \bar{\rho}_m)/\bar{\rho}_m$  in GR:

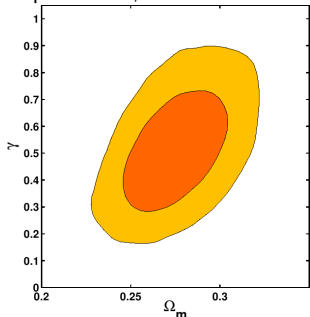
$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = 4G\pi\rho_m\delta$$

Instead, parametrize through

$$\frac{d\delta}{da} = \frac{\delta}{a}\Omega_m(a)^\gamma$$

with  $\gamma \sim 0.55$  accurately reproducing GR.

Rapetti *et al.*, arXiv:0812.2259



XLF+WMAP5+ $f_{\text{gas}}$ +snIa(Union)

$$\Lambda\text{CDM} \quad \gamma = 0.51^{+0.16}_{-0.15}$$

$$w\text{CDM}^* \quad \gamma = 0.44^{+0.17}_{-0.15}$$

$$\text{non-flat } \Lambda\text{CDM} \quad \gamma = 0.51^{+0.19}_{-0.14}$$

\* $w$  is used *only to parametrize the expansion history* in this model

# Conclusions

- ▶  $f_{\text{gas}}(z)$  data for largest relaxed clusters  $\rightarrow$  tight constraints on  $\Omega_m$ ,  $\Omega_\Lambda$  and  $w$  through absolute distance measurements.

$$\Omega_m = 0.27 \pm 0.06 \quad \Omega_\Lambda = 0.86 \pm 0.119 \quad (w = -1.14^{+0.27}_{-0.35})$$

- ▶ Growth of X-ray luminous clusters spanning  $0 < z < 0.7 \rightarrow$  independent constraints on  $\Omega_m$ ,  $\sigma_8$  and  $w$ .

$$\Omega_m = 0.28^{+0.11}_{-0.07} \quad \sigma_8 = 0.78^{+0.11}_{-0.13} \quad (w = -1.4^{+0.4}_{-0.7})$$

- ▶ Combination of  $f_{\text{gas}}$ , XLF, CMB and snla data

$$\Omega_m = 0.269 \pm 0.016 \quad \sigma_8 = 0.82 \pm 0.03 \quad w = -1.02 \pm 0.06$$

- ▶ Combination applied to tests of General Relativity

$$\Omega_m = 0.27 \pm 0.02 \quad \sigma_8 = 0.82 \pm 0.05 \quad \gamma = 0.51 \pm 0.15$$

**This year:** new X-ray and lensing data should provide improvement in both  $f_{\text{gas}}$  and XLF results

**Next few years:** new  $f_{\text{gas}}$  targets and cluster samples from SZ, X-ray, optical surveys